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DESIGN OF PARTIALLY COHERENT AND VORTEX FREE-SPACE OPTICAL SYSTEMS

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Final Report

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14. ABSTRACT

The objective of this 1-year project was to investigate and optimize the design of free-space optical communications systems that employ one or more special beam classes such as partially coherent, vortex, nonuniformly polarized, nondiffracting and Airy beams. Particular attention was focused on the use of incoherent beam arrays with beamlets of special types as well as the use of optical vortices as viable information carriers. Uniformly polarized beam arrays were shown to have appreciable scintillation reduction, and statistics of vortex beam wander were calculated.

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Design of partially coherent and vortex free-space optical communications systems

Final Performance Report

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Award: FA9550-12-1-0007

1. Summary

The objective of this 1-year project was to investigate and optimize the design of free-space optical communications systems that employ one or more special beam classes such as partially coherent, vortex, nonuniformly polarized, nondiffracting and Airy beams. Particular attention was focused on the use of incoherent beam arrays with beamlets of special types as well as the use of optical vortices as viable information carriers. There were plans to study the influence of temporal coherence on the speed and robustness of the communication systems will be investigated, and more speculative such as the performance of special beams in strong scattering and particulate media as well as non-Gaussian correlations of partially coherent fields; these will be pursued in the next grant period.

2. Nonuniformly polarized incoherent beam arrays

Free-space optical (FSO) communications systems typically transmit information via variations in the intensity of light. However, variations in the temperature, humidity and pressure in the atmosphere, turbulent or not, can distort an optical beam on propagation, leading to fluctuations in the intensity arriving at the detector and consequently errors in the transmitted data. These *scintillations* are one of the most significant limitations in the development of robust FSO systems.

Partially coherent beams are generally expected to have lower scintillation than their fully coherent counterparts. A simple explanation of this effect is shown in Fig. 1. A partially coherent beam can be interpreted as an incoherent superposition of multiple independent

beamlets. Though any individual beamlet may not make it to the detector, there is an increased likelihood that some combination of beamlets will; the result is, on average, a more regular distribution of intensity.

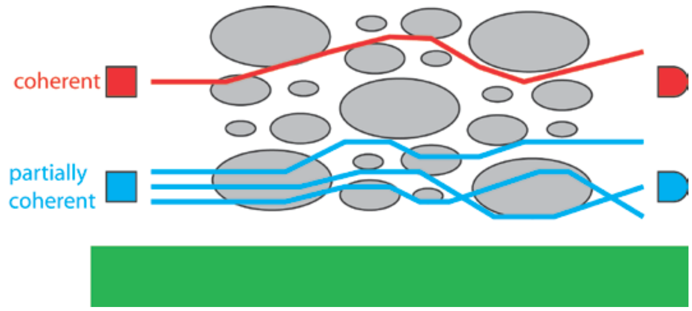

Figure 1. Illustration of the physics behind the improved performance of partially coherent beams in turbulence. A coherent beam sends all of its energy through a single mode, while a partially coherent beam sends its energy through multiple independent modes. The latter is more likely to send a regular amount of energy to the detector.

In the previous grant period, the PI and collaborator demonstrated that a finite array of mutually incoherent beamlets can have scintillation as low as a general class of partially coherent beams [1]. This observation simplifies the requirements for a partially coherent sources for use in atmospheric propagation, as arrays are relatively easy to put together and use. With a fixed number of beamlets, the fundamental limitation of the array is then the scintillation of the individual beamlets. This has now been shown to be reducible using polarization effects.

Polarization is typically not taken into account in beam propagation through the atmosphere, and with good reason: the polarization of a uniformly polarized beam typically does not change under the weak scattering conditions of clear air turbulence. However, a beam which has a nonuniform polarization – a polarization state which depends on the transverse position in the beam – may be mathematically decomposed into two beamlets with orthogonal polarization. Each of these beamlets will propagate differently within the atmosphere, and they will not interfere at the detector. In essence, the nonuniformly polarized beam acts as a two-mode partially coherent source.

The PI and collaborators demonstrated [2] in the previous grant period that such beams can have a significantly lower scintillation than a comparable Gaussian beam: 33% lower. It was then natural to ask whether such a significant reduction would carry over to an array of nonuniformly polarized beamlets.

This idea was investigated in [Publication 1]. An incoherent array of 4 beamlets were designed and their propagation through 2.5 km of moderate turbulence was simulated. The results of these simulations is shown in Fig. 2.

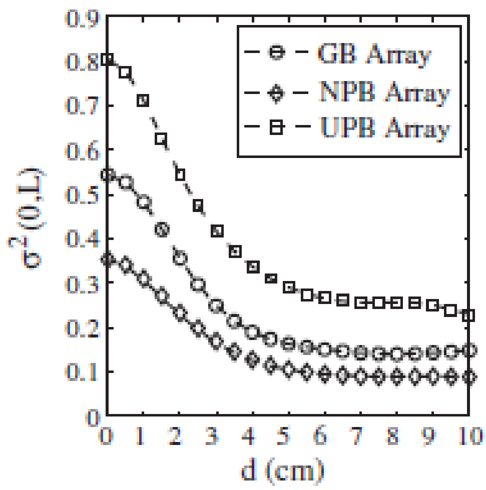

Figure 2. Propagation of a Gaussian beam array (GB), a uniformly polarized beam array (UPB), and a nonuniformly polarized beam array (NPB) through 2.5 km of turbulence, as a function of initial beamlet separation.

The nonuniformly polarized array shows roughly the same 33% reduction in scintillation that the individual beamlet showed, and this holds for a range of source separations and propagation distances, as shown in Fig. 3.

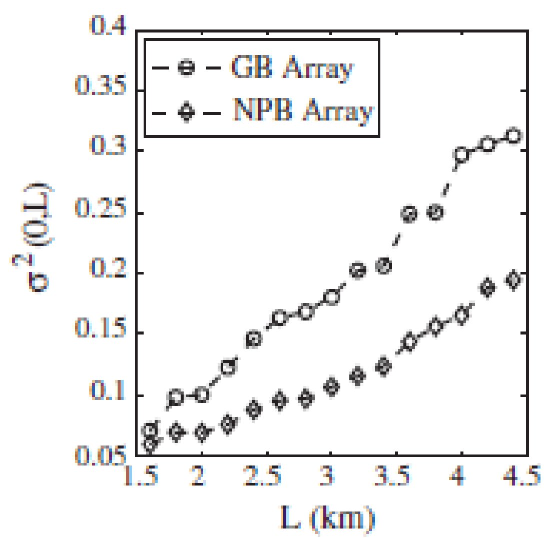

Figure 3. Scintillation of a Gaussian array compared to a nonuniformly polarized array, as a function of propagation distance.

Because a nonuniformly polarized beamlet can be implemented with a relatively simple polarization-sensitive filter, this strategy looks to be a promising one for reducing scintillation without adding significantly to the complexity of the optical source.

3. Vortex beams in turbulence

For several decades now there has been significant interest in the study of optical beams which possess orbital angular momentum. These fields, which possess a central intensity null (phase singularity) about which the phase circulates, are known as optical vortices. An illustration of the cross-sectional intensity and phase of a typical vortex beam, a Laguerre-Gauss beam of order n=0 and m=1, is shown in Fig. 4. The study of such vortices is now a subfield of optics in itself, known as singular optics [3]. The 'order' or *topological charge* of a vortex beam, which is a measure of the field's orbital angular momentum, is a discrete quantity and is conserved under small perturbations of the field. This discreteness and stability has made a number of authors suggest that this topological charge might be used as an alternative carrier of information for optical communications systems [4,5]. In a previous AFOSR grant, the PI and collaborators showed that the topological charge is a robust information carrier, within limits [6].

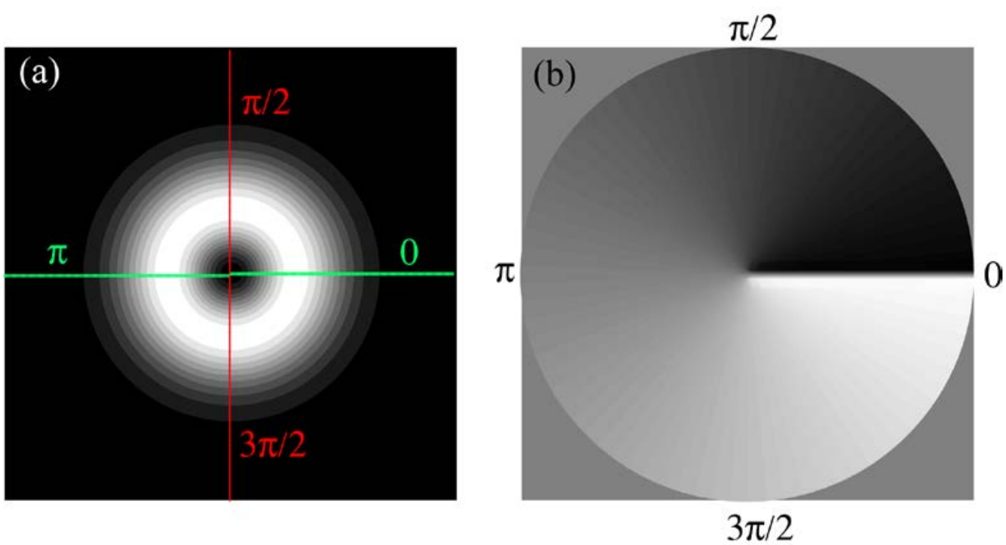

Figure 4. The (a) intensity and (b) phase of a Laguerre-Gauss beam of order n=0, m=1 in the waist plane of the beam. Several equiphase contours are shown in color in (a) for comparison. It can be seen that the phase increases continuously from 0 to 2π as one traces a continuous path around the central singularity.

Many questions remain about the detailed behavior of an optical vortex on propagation through the atmosphere. In particular, there has not been a detailed study of the statistical behavior of the vortex core as a function of propagation distance, and this is an important quantity in trying to determine the optimal size of the source and detector for a given measurement configuration. In [Publication 3], the PI and postdoc theoretically undertook a statistical study of the behavior of such vortex cores; the results are shown in Fig. 5.

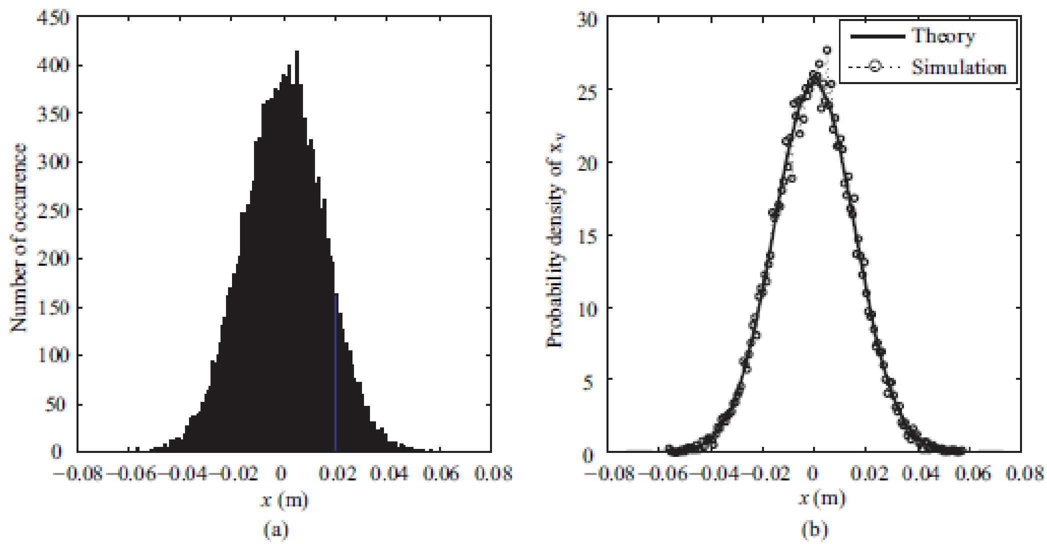

Figure 5. (a) Histogram of vortex positions at 5 km in moderate turbulence, with a source size of 5 cm. (b) Simulated probability density of vortex position, compared with analytical formula for said density.

As one might expect from the law of large numbers, the distribution of positions is of Gaussian form. The exact width of the distribution, however, depends both on the characteristics of the transmission medium as well as the properties of the source. Analytic formulas were derived which allow, in the weak turbulence regime, exact calculation of the probability distribution and its dependence on source and turbulence parameters. Some results of these calculations are shown in Fig. 6. It can be seen that the beam wander depends in a non-trivial way upon the width of the source, and can be minimized with an appropriate choice of parameter. Furthermore, with the probability distribution calculated, it is possible to determine the probability of a successful detection of a vortex based on the detector size.

These results provide more information for use in determining the effectiveness of vortex beams as a communication method in free space propagation, an idea that will be pursued further in the next grant period.

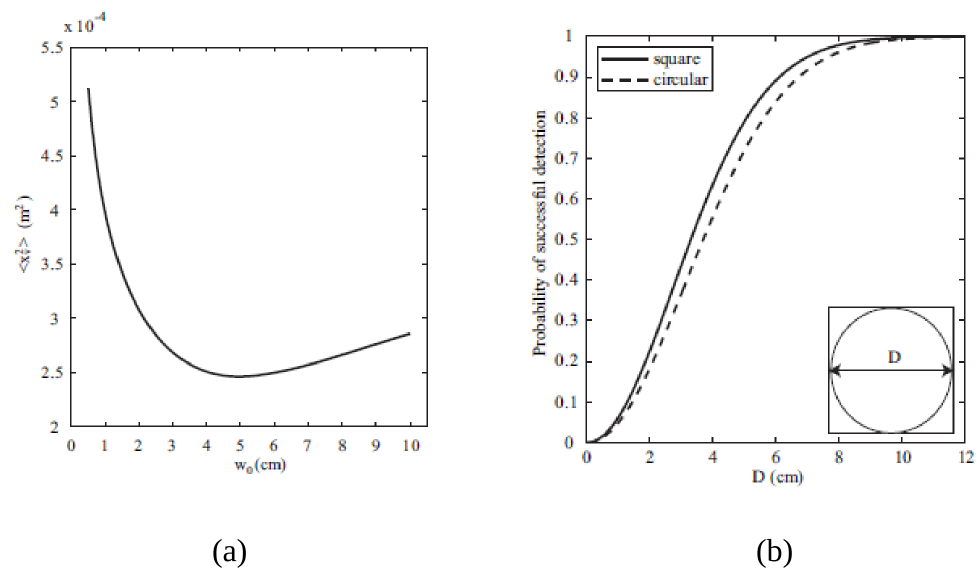

Figure 6. (a) Vortex wander as a function of source width. (b) Probability of detection as a function of detector size.

4. Angular momentum of partially coherent vortex beams

One of the most appealing aspects of optical beams possessing a vortex core is their inherent orbital angular momentum; this angular momentum [AM] also explains in part the robustness of such beams on propagation through turbulence, much like a spinning bicycle wheel is resistant to turning.

On propagation through the atmosphere, a vortex beam becomes, on average, a partially coherent vortex beam. Though the AM properties of coherent beams have been well-discussed [7], there has been no comparable work done for the partially coherent case. In [Publication 2], the PI and a collaborator derived explicit formulas for the angular momentum of a partially coherent, electromagnetic beam. It was shown that the AM can be separated into a spin and orbital part, as in the coherent case. Most notably, it was found that distinct classes of circulating beams exist; this is illustrated in Fig. 7. Two

general classes were considered: vortex beams which are subject to “wander,” such as due to atmospheric turbulence, and so-called “twisted” Gaussian Schell-model beams [8].

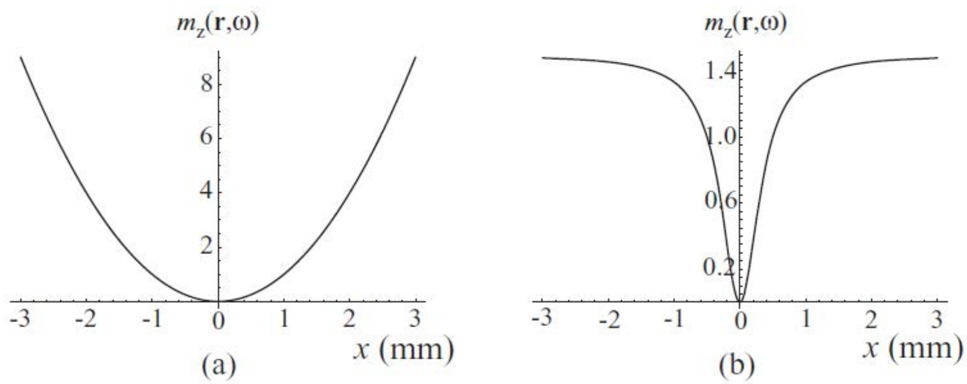

Figure 7. The orbital angular momentum density of (a) a twisted beam, and (b) a vortex beam subject to wander.

The vortex beam possesses two distinct regions of different angular momentum density, a rigid rotator core and an outer fluid-like shell. This angular momentum has the structure of a Rankine vortex, as was predicted for a partially coherent vortex beam some years earlier [9]. Curiously, however, the twisted beam has an angular momentum density that acts as a pure rigid body. This result suggests that there exist different classes of circulating partially coherent beams, and that these different classes might have dramatically different propagation behavior in turbulence.

5. Scattering from particles with semisoft boundaries

With an eye towards future studies of light propagation through particulate media, the PI collaborated with Professor Olga Korotkova on a method to simulate microscopic particles with semisoft boundaries [Publication 4]. This method potentially allows an analytical calculation of light scattering from particles with a range of boundary conditions, as well as hollow particles. It is hoped to apply this result to develop new models for light scattering in clouds and dust.

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Publications produced from grant

[1] Y. Gu and G. Gbur, “Reduction of turbulence-induced scintillation by nonuniformly polarized beam arrays,” Opt. Lett. 37 (2012), 1553-1555.

[2] S.M. Kim and G. Gbur, “Angular momentum conservation in partially coherent wave fields,” Phys. Rev. A 86 (2012), 043814.

[3] Y. Gu, “Statistics of optical vortex wander on propagation through atmospheric turbulence,” submitted to J. Opt. Soc. Am. A.

[4] Serkan Sahin, Greg Gbur, and Olga Korotkova, “Scattering of light from particles with semisoft boundaries,” Opt. Lett. 36 (2011), 3957.*

* NOTE: This paper was published at the start of the project discussed here but was mistakenly labeled with the previous grant number.

Presentations produced from grant

1. Y. Gu and G. Gbur, “Use of Nonconventional Incoherent Beam Arrays for Reduction of Turbulence-induced Scintillation,” OSA Frontiers in Optics meeting 2011 in San Jose, CA.
2. Y. Gu and G. Gbur, “Reduction of Turbulence-induced Scintillation by Nonuniformly Polarized Beam Arrays,” OSA Frontiers in Optics meeting 2012 in Rochester, NY.

3. G. Gbur, “Phase singularities in partially coherent wavefields,” OSA Frontiers in Optics meeting 2012 in Rochester, NY (invited).